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COIL technology development at Boeing

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ABSTRACT

The historical COIL contributions at the McDonnell Douglas Research Laboratory, the Rocketdyne Division of Rockwell International and Boeing's Laser and Electro-Optic Systems organization are briefly described. The latter organization now contains the capabilities of the two heritage organizations. Boeing's new high pressure sealed COIL is also described.

1. INTRODUCTION AND HISTORICAL BACKGROUND

Two industrial organizations participating in the early COIL developments were the McDonnell Douglas Research Laboratory and the Rocketdyne Division of Rockwell International. Both of these are now part of The Boeing Company and their laser and electro-optics capabilities have been incorporated into Boeing's Laser and Electro-Optic Systems organization. MDRL was the first industrial organization (and second only to the Air Force weapons Laboratory [1]) to report a successful COIL [2]. Rocketdyne was the first industrial organization to win a competitive award for COIL development [3]. This heritage has continued unbroken over the intervening years and many contributions to COIL technology have been made by the individual and combined organizations. Boeing continues to be a major force in the COIL community, advancing the technology both incrementally and discontinuously through experiments, testing, and analysis sponsored by U.S. Government contracts and by Company discretionary resources. This paper gives a brief account of that historical background, provides a summary of the highlights of some of Boeing's contributions, and then proceeds to describe Boeing's recent work, which has resulted in the development and demonstration of a new type of COIL laser system.

2. HIGHLIGHTS OF TECHNOLOGY DEVELOPMENT AT BOEING

Over the years since 1978, the organizations and individuals belonging to what is now Boeing's Laser and Electro-Optic Systems organization have explored and developed a huge number of concepts for advancing COIL technology in virtually every aspect of the laser and a broad range of applications. The paragraphs below present a brief sampling of this activity.

2.1 Oxygen Generators

Both at MDRL and Rocketdyne, just about every conceivable type of gas-liquid contact device was explored for $O_2(^1\Delta)$ generators, from spargers, through wetted wall devices, aerosols, and jets, with many variants along the way. Novel chemistry as well as detailed parametric characterization of BHP-Cl_2 chemistry was examined. A recent innovation eliminates the solids formation in BHP, which has plagued many researchers [4].

The first $O_2(^1\Delta)$ generator developed at Boeing used a refrigerated rotating surface as a support for the gas-liquid contact surface. Similar to the modern rotating disk generators, this device had a scraper to remove spent liquid from the rotating surface [3]. Another wetted wall generator configuration which was very successful in the early years employed static commercial mixers with relatively high surface area wetted by flowing BHP, with co-flow or counter-flow Cl_2, with or without diluent. These were scaled by over 1000x in Cl_2 flow and achieved 90% Cl_2 utilization and > 70% BHP utilization in a single pass. A small-scale version of one of these devices, with N_2 diluent added at the exit, was the first to report $O_2(^1\Delta)$ yields in excess of 70%. Boeing also explored a variety of aerosol configurations, coupled to a variety of separators. More recently, the full gamut of high-pressure jet generators with He diluent was explored, with counter-flow configurations being the must successful [5]. The generator used in our new laser is a diluent-free cross-flow jet generator which delivers ~ 20 Torr of O_2 at ~ 65% yield, ~ 90% Cl_2 utilization, and ~ 1 Torr of H_2O. The gas-liquid separation allows only ~ 2% of the gas to exit with the liquid, while the gas product is effectively liquid-free.

2.2 Nozzles

Over the past 25 years, COIL nozzle development has not seen as much attention as $O_2(^1\Delta)$ generator development. The "Classical COIL Nozzle" was developed at Boeing in 1981-83 and has been the standard for helium-diluted COILs. It remains in use virtually unchanged today. The nozzle which we developed for our new laser is a totally different approach, designed for use with heavier diluents, where it can lead to significant improvements in system pressure recovery performance. The two approaches and their differences are illustrated later in this paper.

2.3 Pressure recovery

Conventional and advanced pressure recovery technologies have been developed and used at Boeing over the years. Bank blowers at the outboard ends of the nozzle is a technology that has been successfully adapted to COILs from Gas Dynamic Laser (GDL) and HF/DF chemical laser technology. Likewise, conventional diffusers, with and without sidewall energizers, have been adapted to COIL. Boeing successfully developed an advanced normal shock diffuser technology and applied it to COIL [6, 7]. All of these approaches were applied to COILs using helium diluent. With our new laser, the pressure recovery potential of the cavity exit flow is at least 100 Torr, using conventional diffuser technology.

2.4 Exhaust management

Boeing has used mechanical pumps and ejectors for much of the laboratory development work with COILs. More recently, a large, evacuated catch vessel has proved effective and convenient, and works especially well with a laser like ours, which has a relatively high diffuser exit pressure. In the early years, chemical pump technology based on a variety of reactive materials was explored. Our new laser includes a sealed exhaust system in which cryogenically cooled zeolite is used to adsorb the laser exhaust [8, 9].

3. HIGH PRESSURE SEALED COIL

3.1 Introduction

We refer here to the conventional or classical approach to COIL as that in which the Cl_2 in the generator is diluted by He at significant levels and the I_2 is injected into the generator effluent in the subsonic region of slit nozzles. The injection is accomplished via an array of penetrating jets of I_2 diluted and carried by He. Mixing occurs in the subsonic, transonic and supersonic regions of the nozzle and cavity flow, with much of the mixing completed by the nozzle exit plane. Nozzle expansion typically leads to velocities near Mach 2 in this technology [10]. This approach was developed first at Boeing in the early '80s under company and then U.S. Air Force sponsorship. It has been the basis of most supersonic COIL work until recently. A schematic of a typical COIL based on this technology is shown in Figure 1, where it is described as low pressure COIL technology, based on the diffuser exit pressure of 10-20 Torr.

In contrast, the newer technology described here, developed at Boeing in 1997-99, uses an $O_2(^1\Delta)$ generator with no diluent. The generator effluent is expanded to approximately Mach 1 as it enters the laser cavity. There, I_2 is introduced along with N_2 as a diluent in a supersonic nozzle, which expands the flow to Mach 5 under our typical conditions. This flow, in addition to introducing the I_2, mixes with and transfers momentum to the Mach 1 generator flow and accelerates it, resulting in a mixed Mach number of 3 – 3.5 at the cavity exit. A schematic of a typical COIL based on this technology is shown in Figure 2, where the diffuser exit pressure is shown as 100-200 Torr, leading to the designation of high pressure COIL technology. In addition to the obvious advantages of much higher recovery pressure, this technology also results in a significantly lower static temperature in the cavity, providing kinetic and threshold enhancements to power extraction.

3.2 CFD analysis of nozzle mixing

Although this new technology appears very attractive, it presents a real challenge in achieving good mixing in the short times (and thus short flow distances) required by COIL kinetics. Our approach to developing a solution to this challenge has been to define conceptual nozzle designs and then use iterative CFD analysis and other analyses to determine the best configuration. Slit nozzles were selected to minimize boundary layer losses. Our design goal was to have a nozzle that achieved reasonably good mixing within 8-10 cm of flow length and essentially complete mixing by 20 cm, which was a

nominal power extraction distance. Figure 3 shows the parameters of the selected design in terms of upstream and downstream flows as well as the framework of the calculations.

In order to meet the stringent mixing length target, mixing aids were needed, and their dimensionality was varied to achieve the goal. The nozzle which was designed using this approach is shown in Figure 4. A CFD result for this nozzle is shown in Figure 5, where it is seen that the goal of good mixing by 8-10 cm was achieved. Using flow composition parameters from Figure 3, complete mixing would be represented when the N_2 fraction is 0.83. More detailed discussion of the design analysis has been reported previously [11].

3.3 Cold flow testing of selected nozzle

As a design validation, a test article was fabricated and tested in cold flow. The nozzle bank, shown in Figure 6, contained three ejector nozzles of the same length, spacing, and manufacturing methods as the full laser nozzle. The oxygen generator was represented by a plenum upstream of the nozzle bank. The bank included two full and two half oxygen nozzles to feed the downstream cavity, which was a rectangular duct with no divergence, followed by a diffuser section with straight sidewalls and 6° divergence top and bottom. Pitot probe scans were made in the horizontal direction at three downstream locations. Vertical scans were also made. Some horizontal scan data are included in Figure 6, and show high peak pressures and significant structure at the upstream location (3.2 cm downstream of the nozzle exit plane), while the structure has been largely removed at the most downstream (20.7 cm) location. Elimination of spatial variation in the Pitot pressure is interpreted as indicative of completeness of mixing. This work has been described in more detail previously [12].

In addition to the Pitot scans to evaluate mixing, experiments were conducted to evaluate pressure recovery potential. In these experiments, the valve connecting the experiment to the facility vacuum system was gradually closed while monitoring the pressure at the diffuser exit and the pressure in the straight-walled duct representing the laser cavity. Results are presented in Figure 7, where the cavity pressure is seen to remain constant at about 10 Torr until the diffuser breaks back and the cavity unstarts, which occurs at back pressures between 90 and 100 Torr for the two test cycles shown. This indicates a pressure recovery of 100 Torr, achieved with very conventional diffuser technology. This work has also been reported previously [12].

3.4 Laser system description

Incorporating the selected nozzle design, a hypersonic COIL laser test bed was designed, fabricated, installed and tested [13]. The device, seen in Figure 8, was designated as the 1 mole laser, because the target generator flow was 1 gmol/s of Cl_2, with no diluent. Testing results led to 0.9 gmol/s as the optimum flow for this device. Because the new nozzle concept requires a high pressure iodine source, a new high pressure I_2 vaporizer was developed under contract by General Atomics. This system, capable of delivering I_2 at 100 psia and higher is shown in Figure 9. The exhaust from this new laser contains only O_2 and N_2, with small amounts of H_2O, Cl_2 and I_2. This composition, unlike that from the low pressure technology, which contains large amounts of helium, can be adsorbed by commercial adsorbents. Boeing exploited this feature by adding an adsorber bed to the system, resulting in a sealed laser with no exhaust. The adsorber selected was cryogenically cooled zeolite, also referred to as molecular sieve material. The sealed exhaust system may be seen in Figure 10.

3.5 Laser system testing

The system was highly instrumented, including a large number of pressure and temperature measurements to measure the reactant and diluent flows as well as to characterize the gas and liquid flow through the generator, nozzle, cavity, diffuser and exhaust management system. Flow visualization employed video cameras. A suite of chemical diagnostics helped to characterize the flow composition. Another suite of optical diagnostics was used to measure the outcoupled beam characteristics.

Measurements at the generator exit included P, T, $[O_2(^1\Delta)]$, $[O_2(^1\Sigma)]$, $[Cl_2]$, and $[H_2O]$, which allowed chlorine utilization and $O_2(^1\Delta)$ yield to be determined. Another measurement in the BHP effluent allowed its gas content to be determined. Optical emissions at the generator exit and in the laser cavity were collected using the fiber bundle arrangement shown in Figure 11, which allowed simultaneous recording of filtered emission (in-band emission) for $O_2(^1\Delta)$ - $O_2(^3\Sigma)$, $O_2(^1\Sigma)$ - $O_2(^3\Sigma)$, as well as resolved emission using visible and infrared optical multichannel analyzers (OMAs). Some spectra

from these OMAs are shown in Figure 12. The performance of the oxygen generator, averaged over all of the 0.9 gmol/s tests, is summarized in Figure 13.

Optical bundles were also positioned to collect emission from the cavity and an example visible wavelength OMA spectral record with time evolution is shown in Figure 14. Early in the test, the same O_2 emission features as shown in Figure 13 are evident. As the I_2 is turned on and its flow ramped up, the $I_2(B)$-$I_2(X)$ emission dominates this spectral region, but the influence of pooling on $[O_2(^1\Sigma)]$ can be seen.

The diagnostic suite to outcouple a beam and to characterize the beam included a resonator, a calorimeter, a fast flux monitor, and a mode footprint monitor. These may be seen in the layout of Figure 15 and the photographs of Figure 16. The laser resonator was a half-symmetrical stable resonator with a partially transparent dielectric on a transparent flat substrate and a high reflectivity dielectric on a transparent spherical substrate. Total energy in the high power beam was measured using a full-beam, full-power calorimeter. A full-beam sample of the power leaking through the high reflectivity mirror was measured by a fast flux monitor, whose signal was converted to power by normalization of the integrated signal to the energy measured by the calorimeter. The mode footprint (beam footprint) was recorded using an infrared video camera viewing a diffuse scatter plate located behind the high reflectivity resonator mirror.

Representative power vs. time records for four tests are shown in Figure 17. Three of the tests involved increasing the I_2 flow and show attendant power increases. In the fourth, the I_2 flow was constant and the sealed exhaust system was operating. In some of the power records, transient events are seen. These were determined to be transient increases in extracted power and indicate that significantly more power is available in the flow than we were able to extract in a steady-state fashion. Comparisons of the new laser performance with helium diluent results for other lasers are shown in Figure 18, where chemical efficiency is plotted against the well-known $P \cdot \tau$ parameter. The steady-state performance is comparable with the best of the helium data base, while the transient results, if they could be achieved in steady state, would represent a significant improvement.

Finally, the new laser, because of the I_2 delivery and injection method, results in mixing within the supersonic cavity flow, in contrast to the conventional low-pressure helium diluent technology, where the flow enters the cavity in a nearly premixed state. This latter condition has required developers to deal with the well known sugar-scoop intensity problem. The mode footprint images, shown in Figure 19, reveal that the new laser has a uniform beam intensity and does not exhibit a sugar-scoop effect.

4. SUMMARY

Boeing's Laser and Electro-Optical Systems organization, and its predecessor Rockwell International and McDonnell Douglas organizations, have been contributing to COIL technology advancements for only slightly less than the 25 years being commemorated by this session. These contributions have come in nearly every aspect of the technologies needed to bring this laser from the laboratory to useful application in a variety of areas. A few of these contributions in the oxygen generator, nozzle, pressure recovery and exhaust management areas were highlighted at the beginning of this paper. The conventional low-pressure subsonic-injection nozzle is probably the most enduring of these earlier contributions.

The ejector nozzle, recently developed for the high pressure sealed COIL, represents both a continuation of Boeing's legacy as the leader in COIL nozzle development as well as a departure from the past, enabling COIL applications that would not have been possible with the earlier technologies. At the same time, Boeing's high pressure sealed COIL represents integration and demonstration of a COIL system incorporating a very advanced high pressure, high performance $O_2(^1\Delta)$ generator; the new nozzle; and a sealed exhaust system. The result is an operating laser system test bed that is new from end to end. The performance of this laser, measured by chemical efficiency, is competitive with the best of the low-pressure helium-based technology, and indications are that significantly more power is available.

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FIGURES

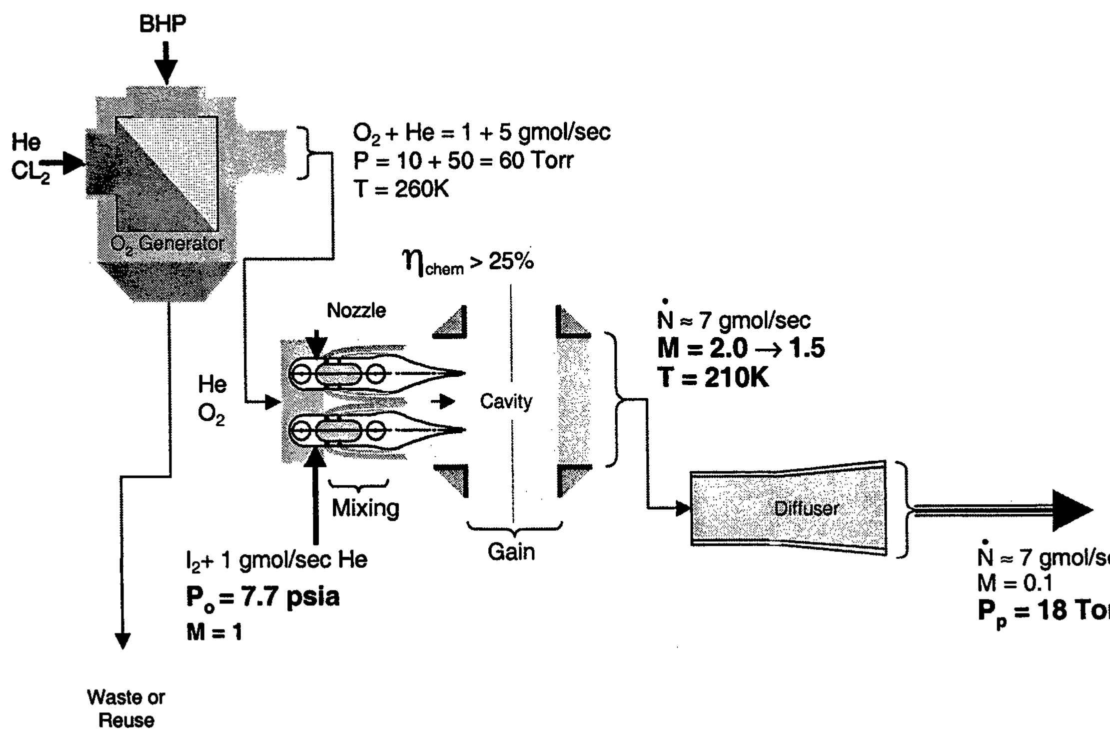

Figure 1. Laser System Based on Low Pressure COIL Technology

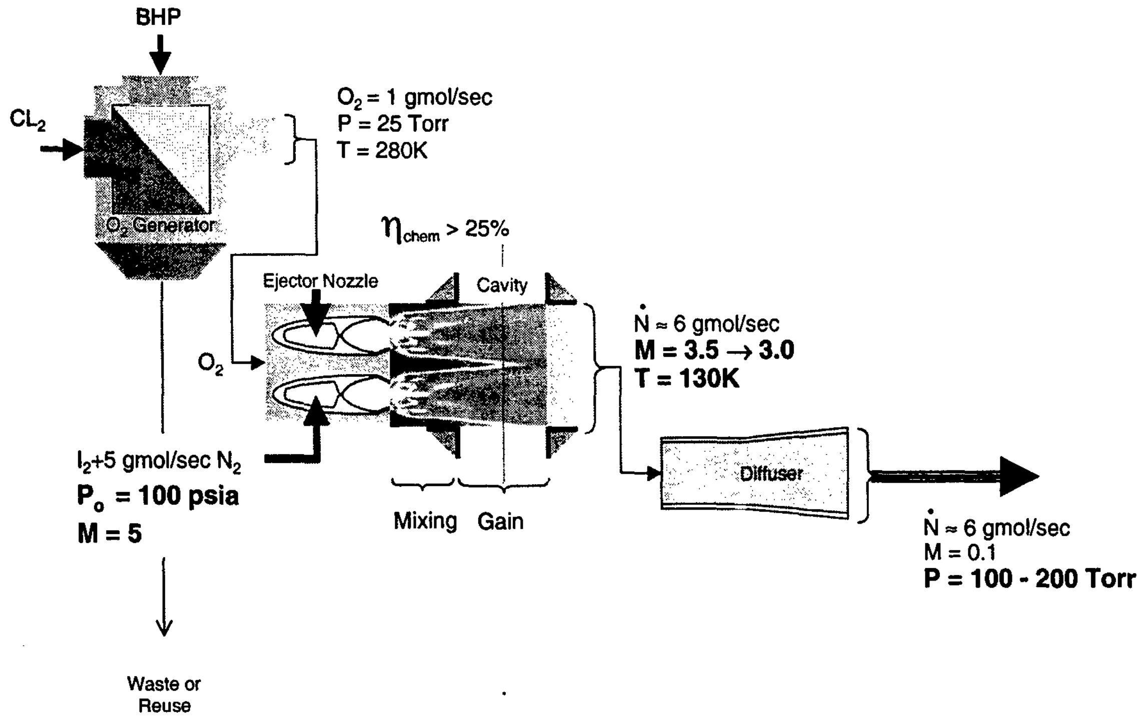

Figure 2. Laser System Based on Next Generation COIL High Pressure Technology

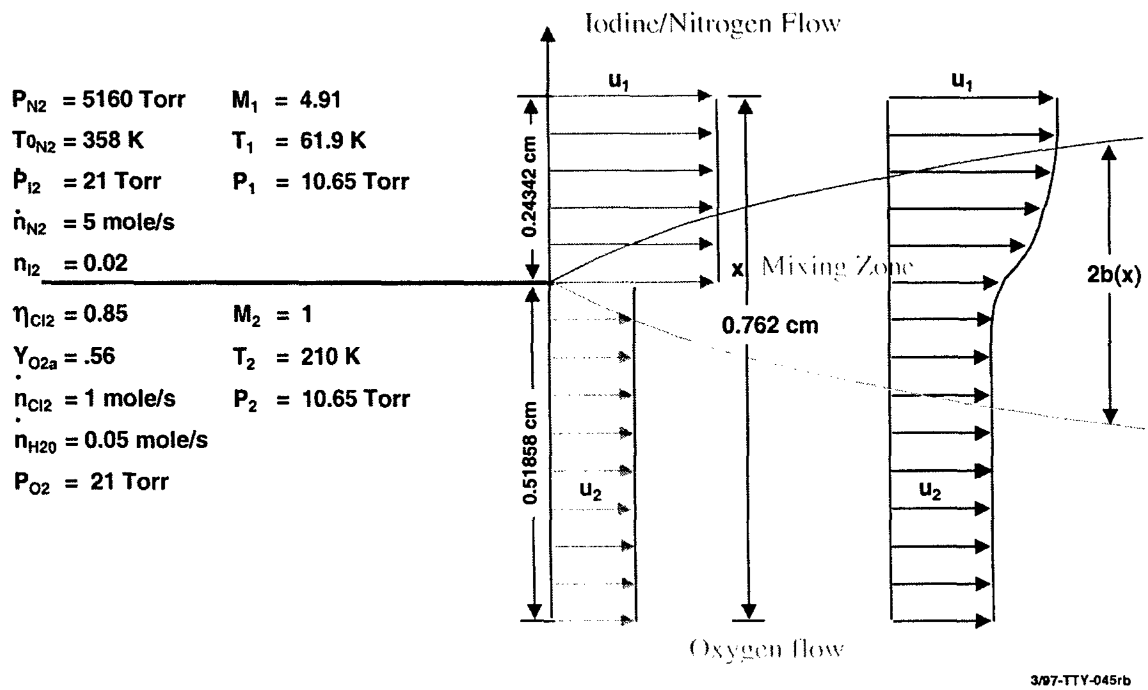

Figure 3. Supersonic Shear Layer Mixing in High Pressure N_2 Diluent COIL

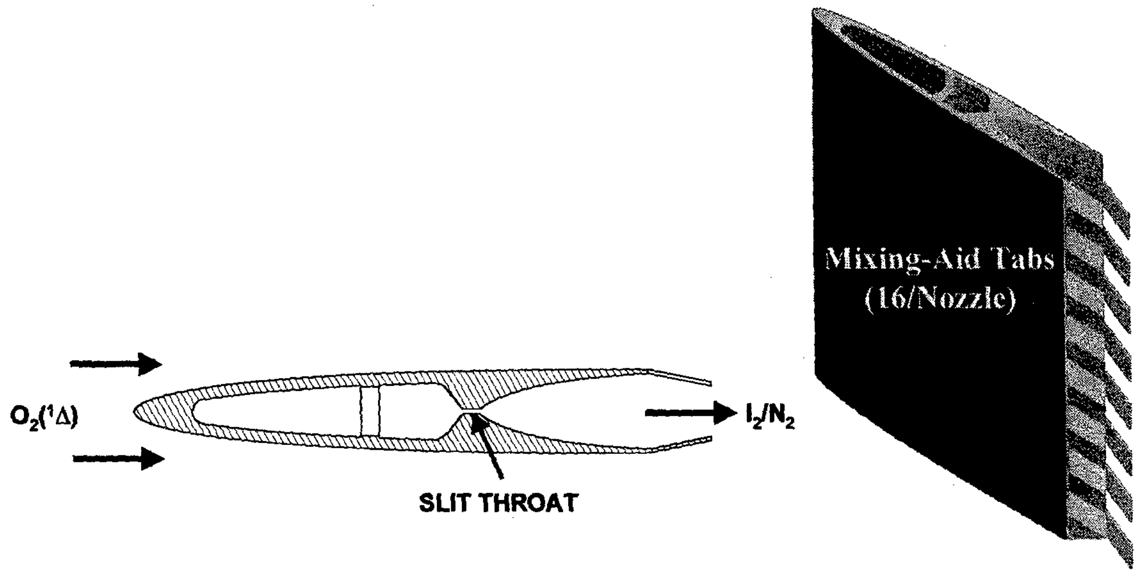

Figure 4. Nozzle Design Based on CFD Analysis

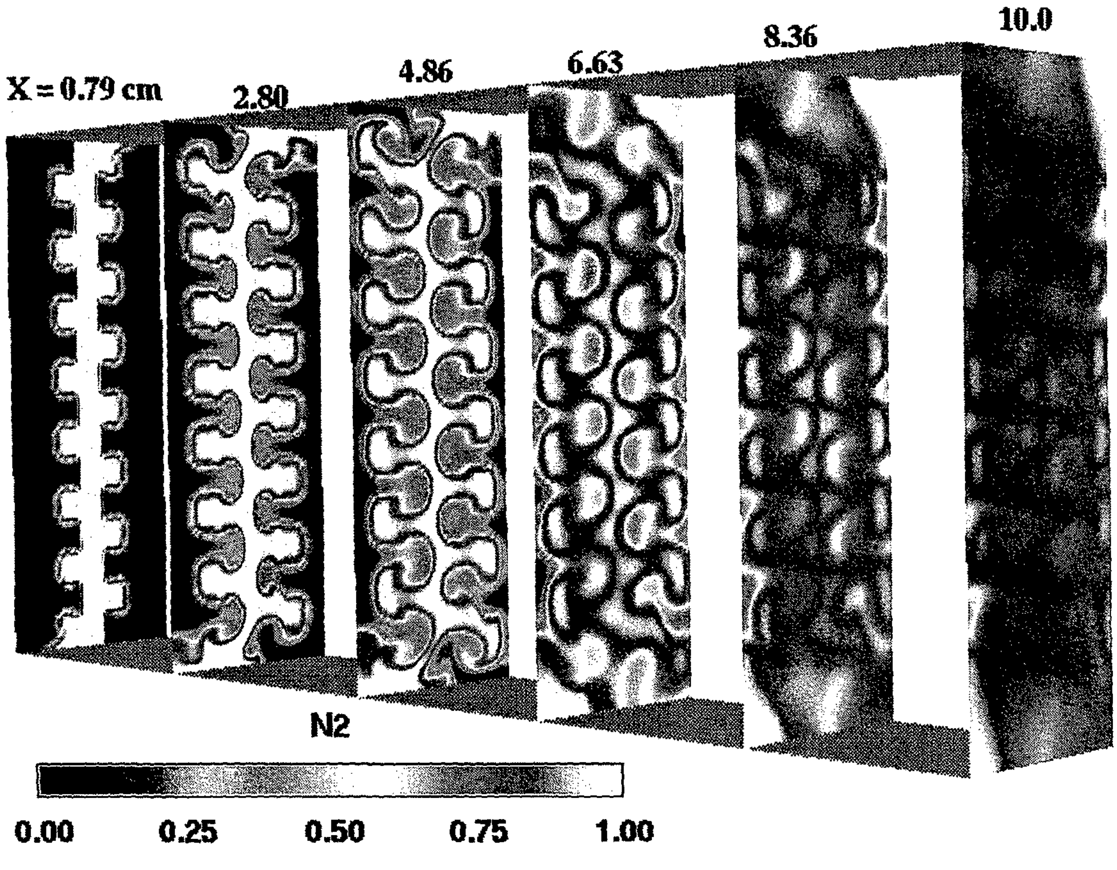

Figure 5. CFD Results for Selected Nozzle Show Excellent Mixing

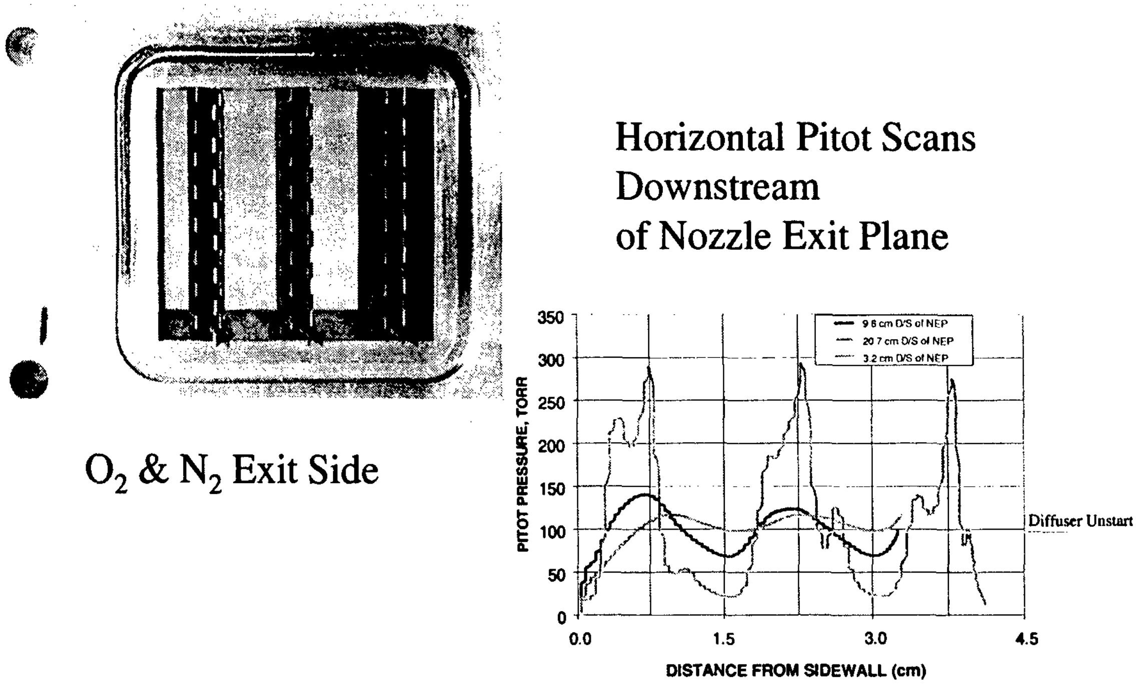

Figure 6. Cold Flow Testing of 3 Blade Test Article Confirms CFD Mixing Results

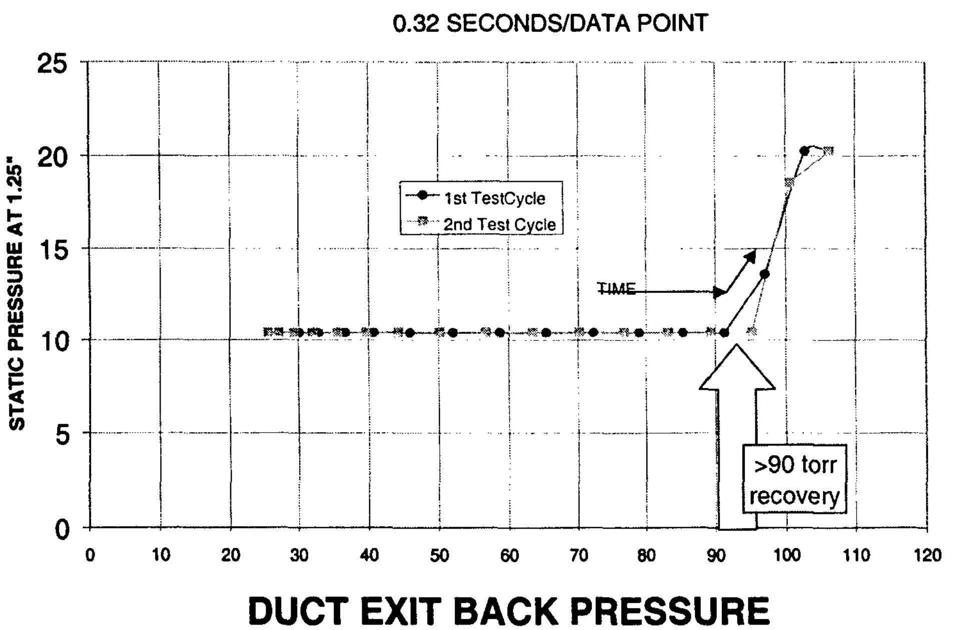

Figure 7. Diffuser Unstart Tests Show ≈ 100 Torr Pressure Recovery

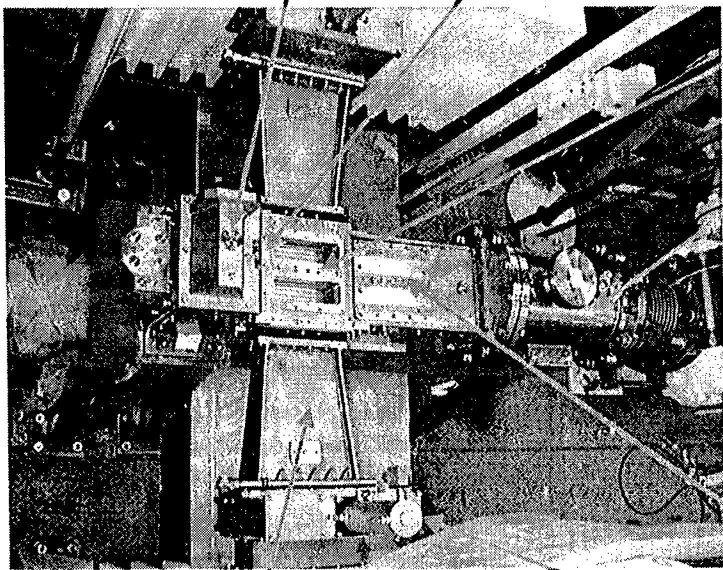

Figure 8. Boeing's New High-Pressure, High Mach Number COIL

Vaporizer (Outside) **Vaporizer (Inside)**

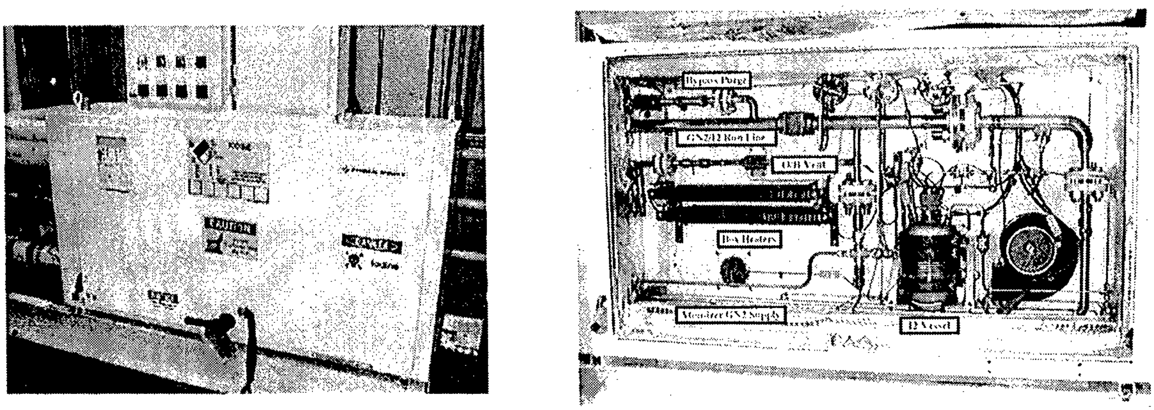

Figure 9. High Pressure Iodine Supply System, Developed for Boeing by General Atomics

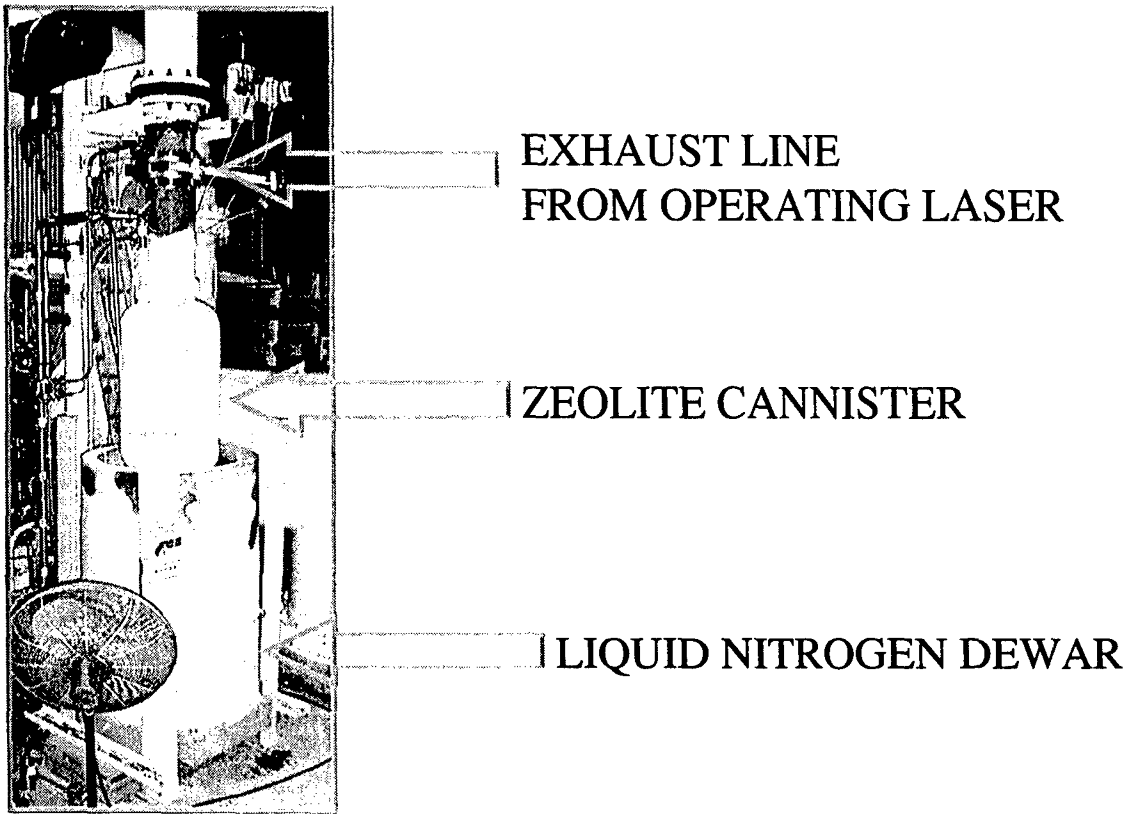

Figure 10. Sealed Exhaust System for Boeing's New High Pressure Sealed COIL

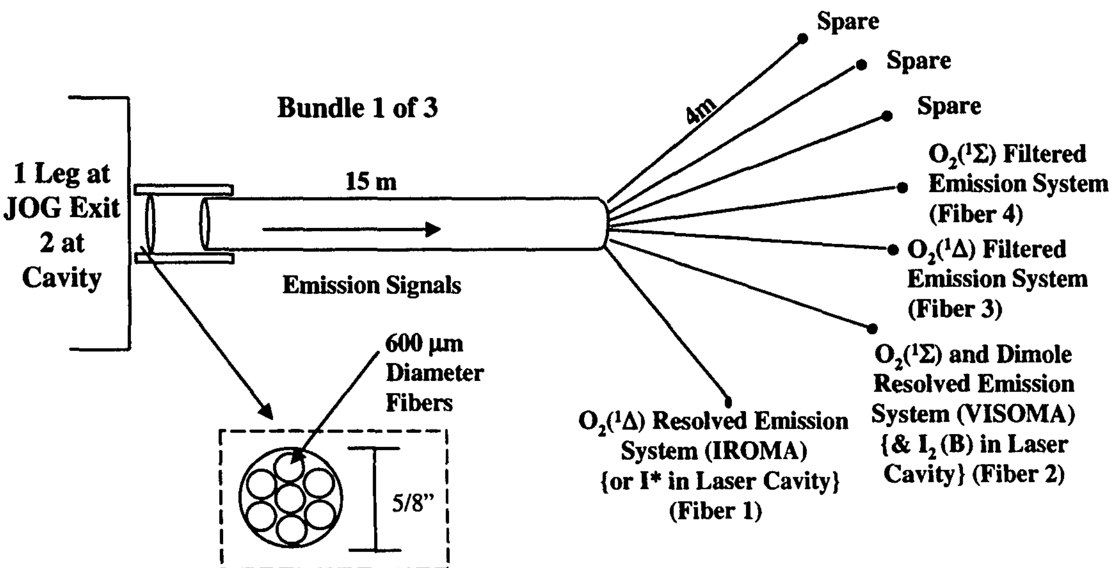

Figure 11. Fiber Bundle Approach for Simultaneous, Co-located Chemical Diagnostic Measurements

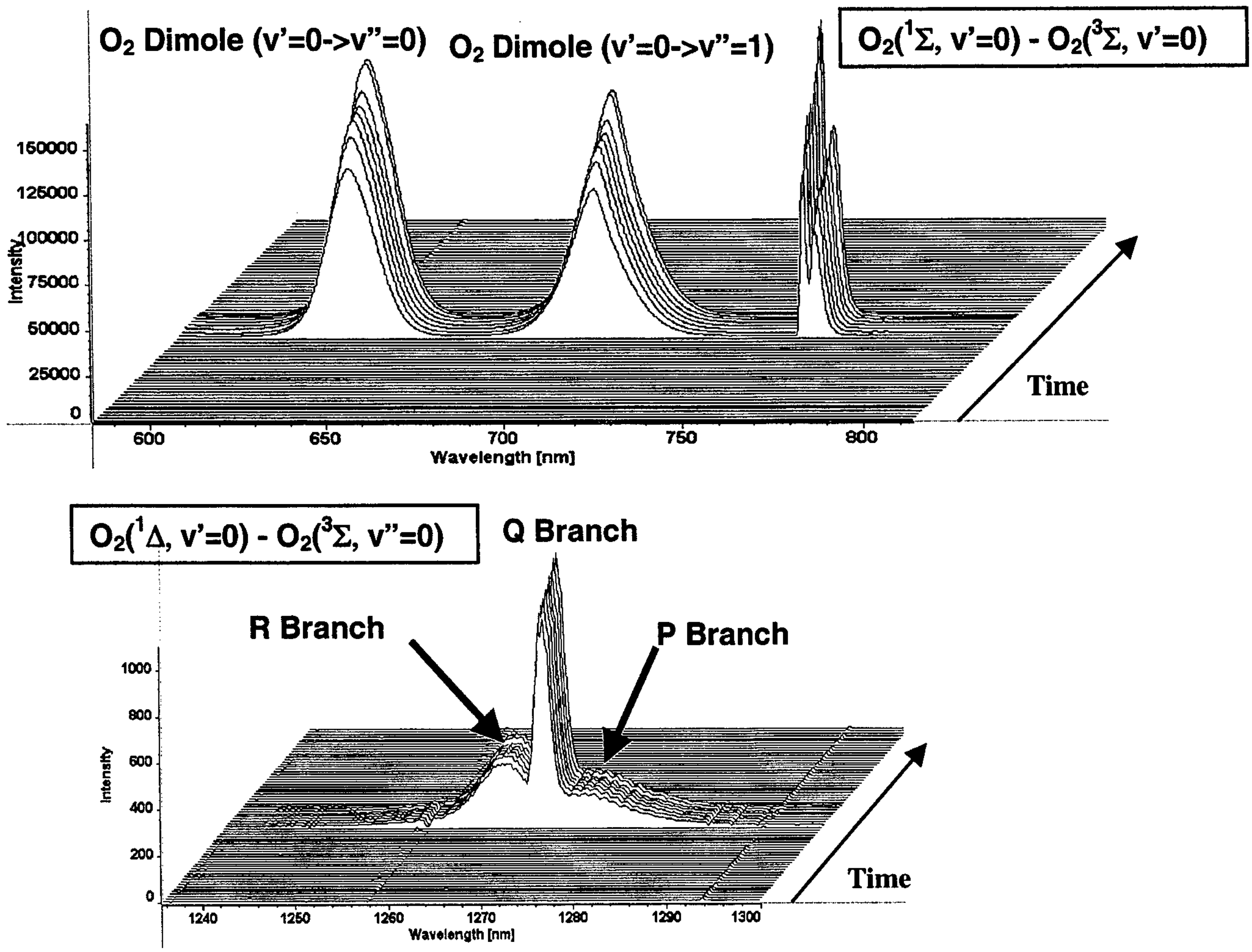

Figure 12. V isible and Infrared Optical Multichannel Analyser Spectra of Generator Outlet

- **Outlet Pressure = 21 Torr, Controlled by Nozzle**
- **Outlet Temperature = 342 K**
- **Chlorine Utilization = 0.89, Cl_2 Pressure = 2.2 Torr**
  - **From absorption/scatter measurements: average windows, average T**
  - **Consistent with BHP temperature rise**
  - **Consistent with mass spectrometry via O_2 / N_2**
- **$O_2(^1\Delta)$ Yield ≈ 0.6 - 0.7**
  - **From filtered and OMA emission: average [Cl_2], average T**
  - **Consistent with JOG Raman measurements: 0.64**
- **H_2O pressure = 1.4 Torr (1 Torr Typical)**
  - **From absorption measurements: average T**
- **Gas Bypass with BHP Effluent, ≤ 2%**
- **Liquid Content of Gas Product - nil**

Figure 13. $O_2(^1\Delta)$ Generator Performance Averaged Over All 0.9 gmol/s Tests

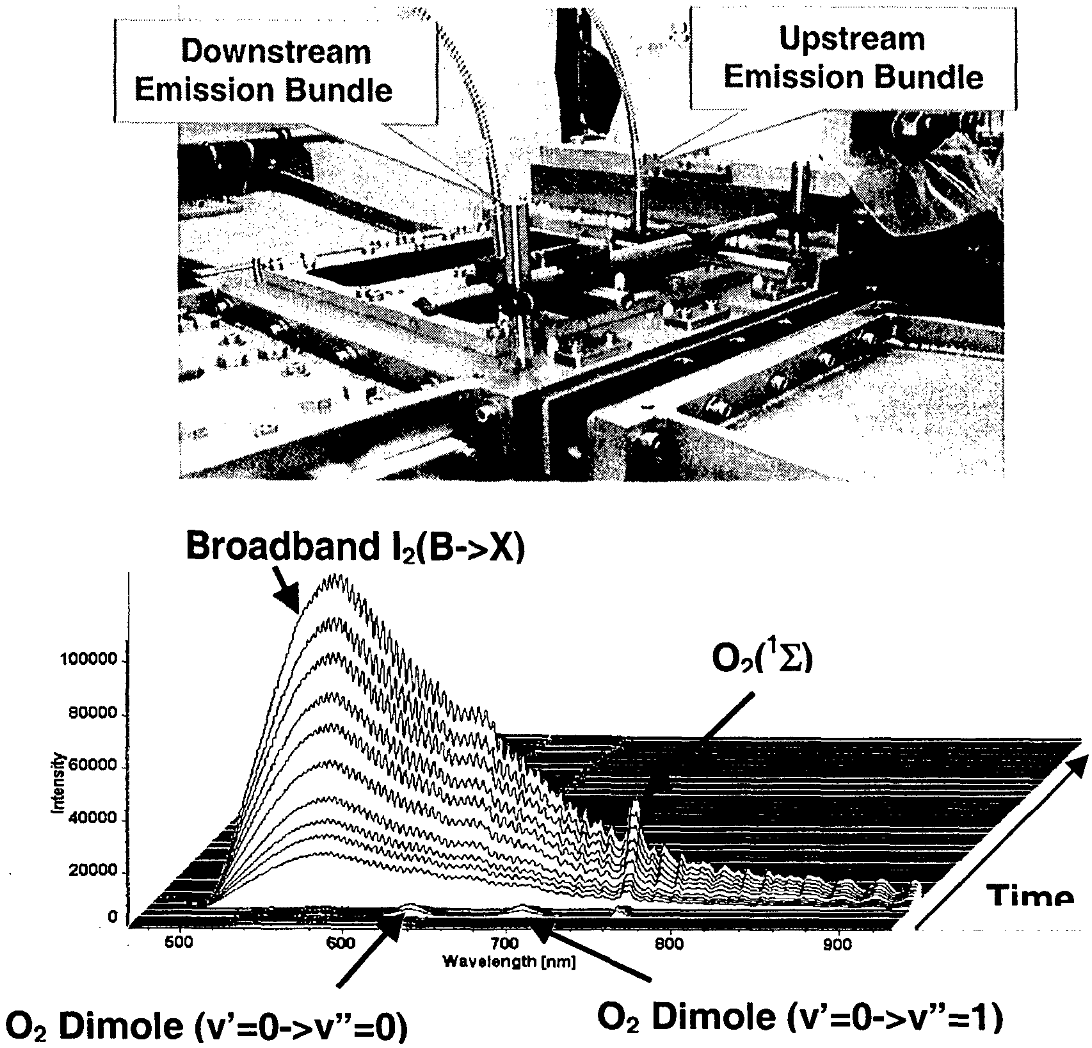

Figure 14. Cavity Visible Emission Spectra

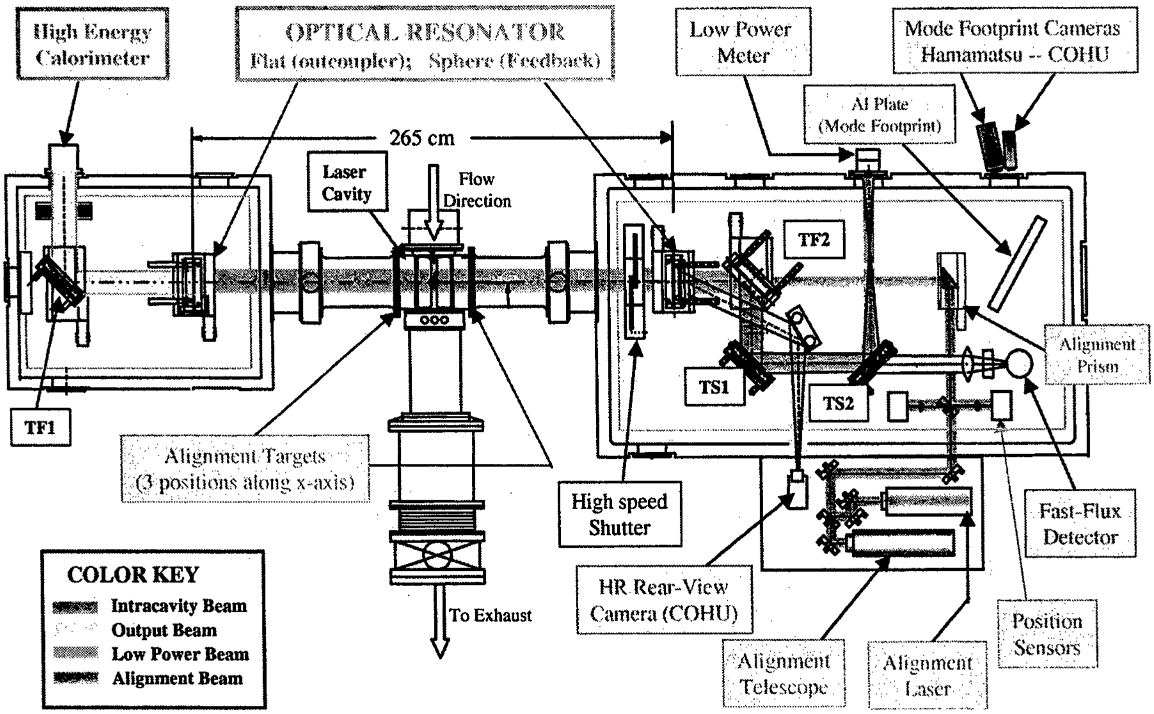

Figure 15. Layout of Optical Diagnostics System, Including Resonator

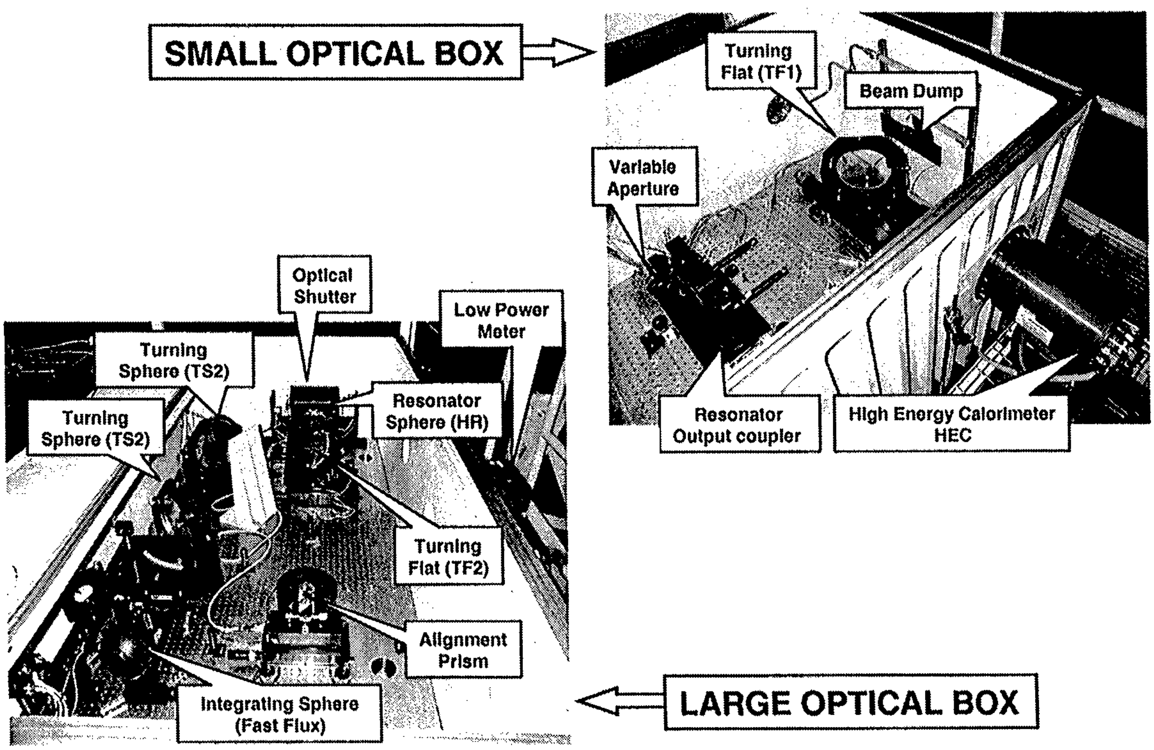

Figure 16. Interior of Optical Boxes, Showing Optical Diagnistics

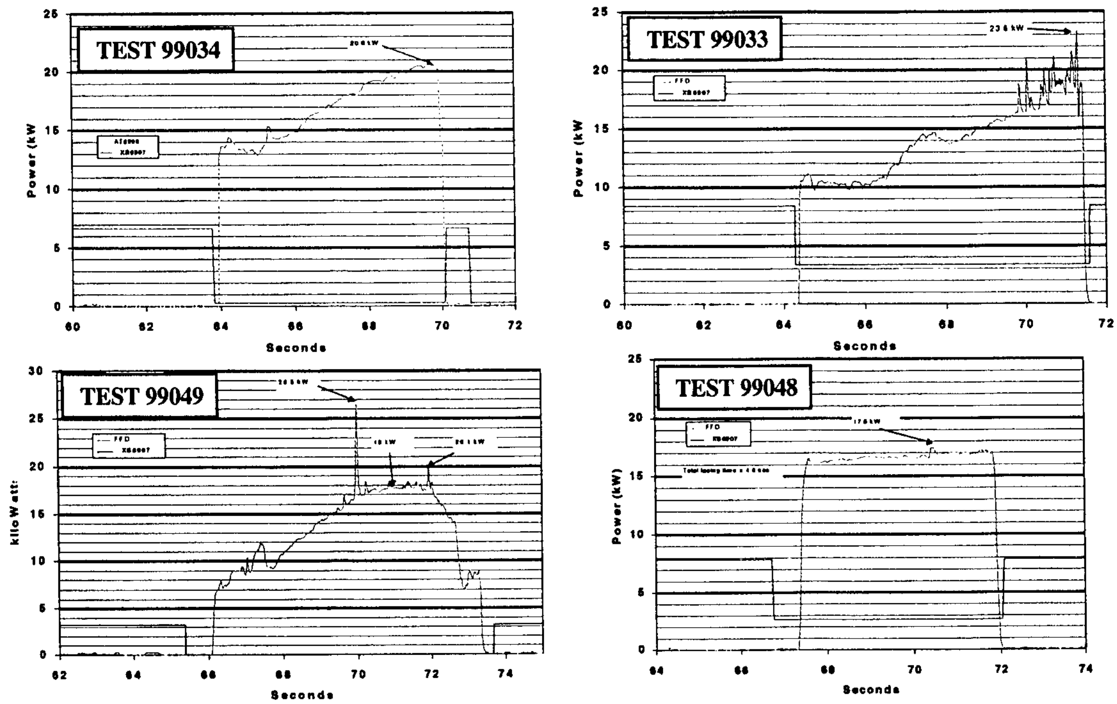

Figure 17. Some Typical Power vs. Time Scans from the Fast Flux Monitor

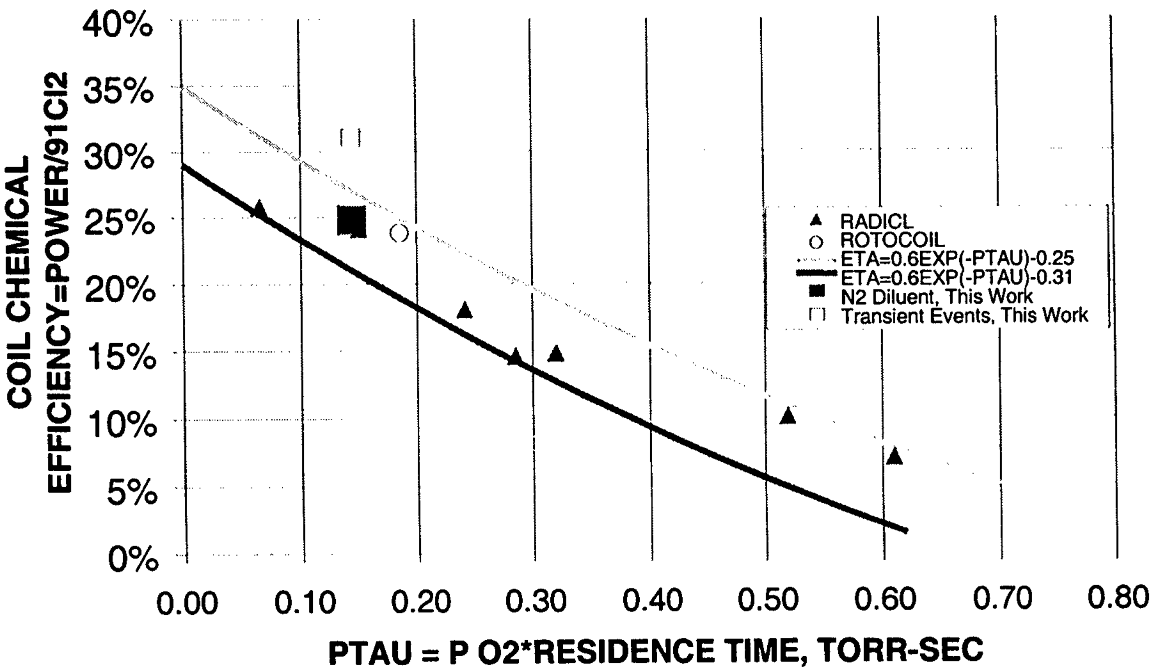

Figure 18. New N_2 Laser Performance is Comparable with Helium Diluent Chemical Efficiency

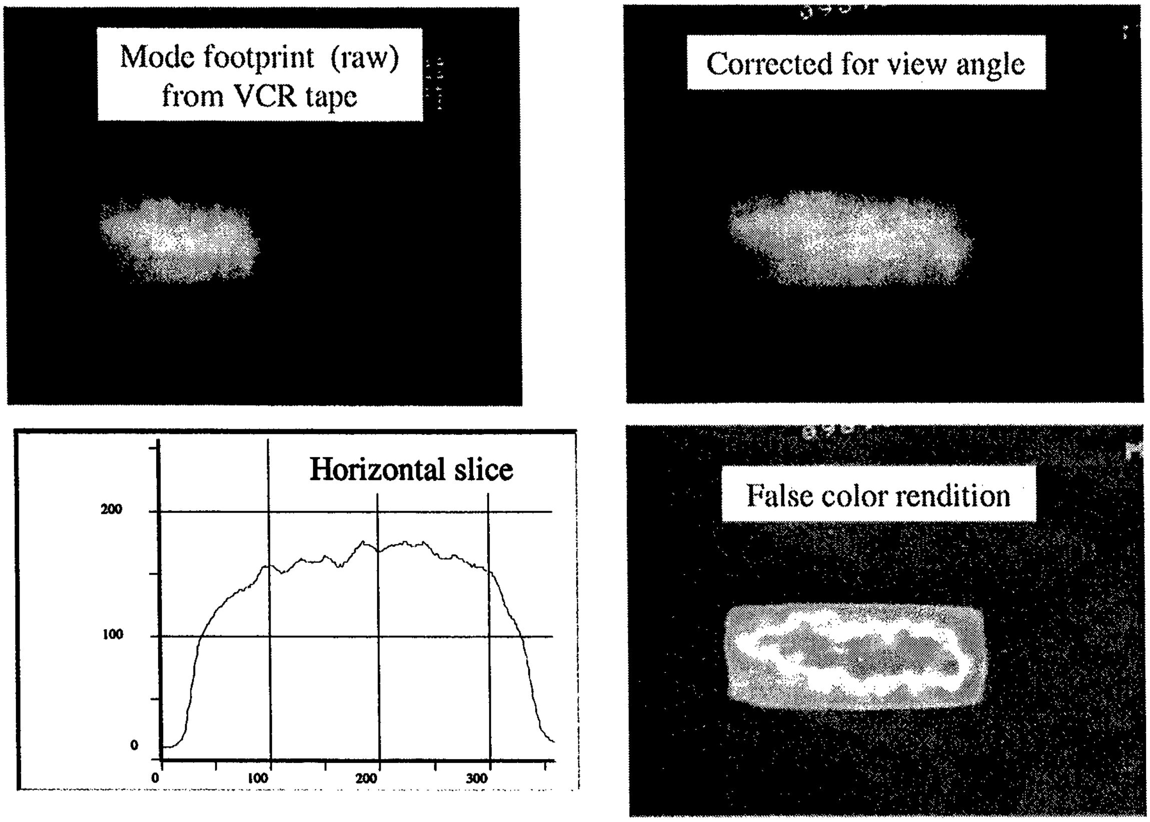

Figure 19. Results from Mode Footprint Camera Show Uniform Beam Intensity